

PROCEEDINGS OF THE ROYAL SOCIETY.

SECTION A.—MATHEMATICAL AND PHYSICAL SCIENCES.

An Experimental Determination of the Critical Electron Velocities for the Production of Radiation and Ionisation on Collision with Argon Atoms.

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In the 'Proceedings of the Royal Society' for 1919 (A, vol. 95, p. 408) we have given an account of an investigation of the effects of electron collisions with helium atoms. The apparatus and method there described have been somewhat modified, and applied to a similar investigation with argon. With this gas Franck and Hertz* came to the conclusion that ionisation occurs when the velocity of the colliding electrons is raised to 12 volts, but the method of experimenting used by them was not able to distinguish between ionisation of the gas and the photo-electric effect of radiation produced by the collisions.

The main features of the apparatus used in the present research† have been described in the earlier paper; the modifications introduced will be seen by reference to the diagrammatic view in fig. 1. A short tungsten filament, F, which could be heated to incandescence by an electric current, was used as the source of electrons. This was supported horizontally and about 1·5 mm. below the top of the platinum thimble, E, which was plane and circular, and had at its centre a circular hole 1·5 mm. in diameter.

* J. Franck and G. Hertz, 'Deutsch. Phys. Ges. Verh.,' vol. 15, p. 34 (1913).

† I am indebted to the Government Grant Committee of the Royal Society for the means of purchasing some of the apparatus and materials used in this research.—F. H.

The platinum thimble was made out of thin sheet, and just fitted into the lower glass tube of the apparatus. Thus electrons from the glowing

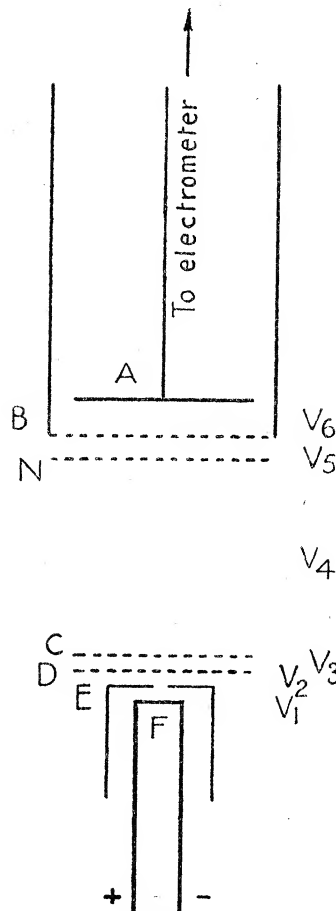


FIG. 1.

filament could only get into the ionisation chamber through the small hole, and it was hoped that this device would approximate to an equipotential source by limiting the effective emission to that coming from a small area at the middle of the filament. In the figure, D, C, N, and B are circular pieces of fine platinum gauze, of which N has been introduced since the earlier experiments with helium. In order to make the beginning of ionisation and radiation well marked, even at low pressures, the space in which these can occur was made larger in the present investigation, the distance between the gauzes C and N being 3 cm., as compared with a corresponding distance of 1 cm. in the earlier experiments. As before, the collecting electrode A was of platinum, and was suspended inside a platinum cylinder, within which it could be raised or lowered over a range of several centimetres. All the platinum used in the apparatus was carefully cleaned by boiling for many hours in strong nitric acid before being fitted into position.

The two gauzes C and D were used in addition to the platinum thimble, E, in order to keep the emission from the filament

constant as the voltage accelerating the electrons into the ionisation chamber was increased, and also to limit the range of velocities among the electrons employed. To this end a constant accelerating potential difference, V_1 , was applied between the negative terminal of the filament and E, and a constant *retarding* potential difference, V_2 , a little less than V_1 , was applied between E and D. Thus, if the screening effect of the gauzes is complete, the same number of electrons, with the same velocities, should reach the gauze D however the fields above this gauze are varied. The variable part of the accelerating voltage (V_3) was applied between the gauzes D and C which are 2 mm. apart. In some of the later experiments it was desired to have a

larger electron current through the ionisation chamber without unduly raising the temperature of the filament, and in these experiments a small constant accelerating field was used between E and D instead of the retarding field mentioned above, so that the full emission from the middle of the filament was used.

As in the experiments with helium, the apparatus was wrapped round by many turns of wire, through which an electric current of from 1.5 ampères to 2.0 ampères was sent during the observations. In this way a strong magnetic field parallel to the axis of the tube was produced, which prevented the stream of electrons from spreading laterally.

The argon supplied to us contained about 15 per cent. of nitrogen. This was removed by sparking between platinum electrodes with an excess of oxygen. During this process the gases were enclosed over a solution of potash in water, and oxygen was obtained as required by electrolysis of the water. The sparking was continued for about 100 hours after the volume of the gas had become constant, and the excess of oxygen was finally removed by heating spirals of copper wire in the mixed gases. Some of the argon was then drawn off by means of a stopcock into a highly exhausted glass globe, which it entered through a U-tube immersed in solid carbonic acid, so as to remove the water vapour from the gas. The glass globe was then sealed off, and the argon it contained was used in the first experiments. By turning a stopcock, it was allowed to pass along a fine capillary tube, from which it entered the apparatus, at the level of the gauze C, through a U-tube immersed in liquid air. The argon remaining in the sparking tube was again sparked with oxygen for a period of three weeks. The excess of oxygen was then removed by phosphorus, and the argon was transferred to a second storing vessel and used in the later experiments. Similar results were obtained with the two specimens, from which it may be concluded that both specimens were pure. The spectrum of the gas was observed by means of a small vacuum tube attached to the apparatus. Only the argon lines were visible, but the spectroscopic test is not a very delicate one, for we were unable to detect nitrogen spectroscopically in a sample of argon which contained 3 or 4 per cent. of nitrogen.

Before beginning the experiments, the apparatus was pumped out by a mercury vapour pump and the residual gas removed as completely as possible from the filament, electrodes, and glass walls of the apparatus, by long-continued heating and pumping. During the observations, argon was slowly streaming through the apparatus, the pressure of the gas being adjusted both by the tap on the storage bulb and by the pumps. As a series of observations usually occupied about an hour, it was impossible to

maintain the pressure constant throughout, but the variations in pressure were not large and they were gradual—a steady increase or decrease, according as the pump was working too slowly or too quickly; thus no discontinuity was caused in the curves obtained.

*Preliminary Experiments to Obtain Approximate Values of the Critical
Electron Velocities.*

In these experiments the fields V_1 and V_2 were constant, and the energy with which the electrons reached the level of the gauze C was varied by increasing the accelerating field V_3 . The gauzes C and N were connected together so that, unless loss of energy by collisions with argon atoms occurred, the electrons would maintain the velocity they have at C over the distance C N. Thus when the velocity reaches a critical value an electron is able to produce radiation or ionisation if it collides with an argon atom in this space. As the distance between C and N is 3 cm. a considerable effect should be produced even at pressures as low as 0.01 mm., for most of the electrons entering the space C—N would make collisions with argon atoms. The electrons which pass through the gauze N encounter an opposing electric field, sufficiently strong to prevent any of them from reaching the gauze B, so that none can pass to the plate A, and the electrometer should therefore give no indication of a current until the collisions with argon atoms in the space C—N give rise to either radiation or ionisation. The method used to distinguish between these two effects is that used by Davis and Goucher* in their experiments with hydrogen and other gases, and by ourselves in the experiments with helium. It consists in observing the effect of reversing the direction of the small difference of potential V_6 between the gauze B and the collecting electrode, A, and thus reversing the current in this space due to the photo-electric action of any radiation which is produced by the electron collisions.

It must be noticed that since the field V_4 between the gauzes C and N is zero, the detection of ionisation by collisions in this space depends upon the positive ions formed diffusing into the space above the gauze N. Those which do so will be driven by the field V_5 towards the collecting electrode, but they may be retarded or even prevented from reaching it by the field V_6 . If the gauze B is charged negatively to the plate A, radiation acting photo-electrically upon B will cause the electrometer to indicate a negative current. A field between B and A in this direction will, however, tend to retard any positive ions which pass through the gauze B, but, provided this field, V_6 , is small, and the pressure of the argon not too high, the positive

* Davis and Goucher, 'Phys. Rev.,' vol. 10, p. 101 (1917).

ions should be able to reach the collecting electrode against the retarding field. Thus, with this arrangement of the fields, the electrometer should indicate a positive or a negative current according as the effects of ionisation or those of radiation predominate. Series of observations of the current to the collecting electrode with different accelerating voltages, taken with the gauze B at a negative potential compared with the plate A, will be referred to as (I—R) series. If the gauze B is at a positive potential compared with the collecting electrode, positive ions getting through this gauze will be further accelerated towards that electrode by the field V_0 , and since the photo-electric effect of any radiation produced will now tend to make the plate A lose electrons, both radiation and ionisation will tend to cause the electrometer to indicate a positive current. For this reason curves obtained from observations with B positive to A will be referred to as (I + R) curves.

Typical examples of (I—R) curves are given in curves I and II of fig. 2. Both sets of observations showed a negative current beginning between 9 and 10 volts accelerating potential difference. This indicates that when the applied accelerating potential difference reaches this value, the electrons have sufficient energy to produce radiation on colliding with the argon atoms. It will be seen that the negative current due to radiation increases steadily until the point marked A on each curve; at these points the increase ceases and the negative current begins to decrease, showing that at this stage positive ions are reaching the collecting electrode. It will be observed that the accelerating voltage at which this change occurs is very different in the two curves given. In curve I it is 16.4 volts, while in curve II it is 14.4 volts. The main difference in the conditions under which the two curves were obtained is that in the case of curve I, the pressure of the argon gradually rose from 0.078 mm. to 0.099 mm. during the observations, whereas in the case of curve II the pressure measured by the gauge was much lower varying from 0.00197 mm. to 0.00175 mm. during the experiment. In both cases the distance of the collecting electrode A, from the gauze B, was 1 cm., and the difference in the positions of the point A on the two curves is no doubt explained by the greater difficulty experienced by the positive ions in reaching the plate at the higher pressure. These curves may, therefore, be taken as indicating that collisions resulting in radiation first occur when the potential difference accelerating the electrons has a value between 9 and 10 volts, and that ionisation of the argon is produced when this potential difference is increased to about 14.4 volts. In other experiments the presence of positive ions was detected with accelerating voltages slightly less than this, so that it is probable that even in the case of curve II, positive

ions are not reaching the collecting electrode until the velocity of the electrons has been raised above the value at which they are first formed.

Another point to which attention must be called is the sharp upward bend

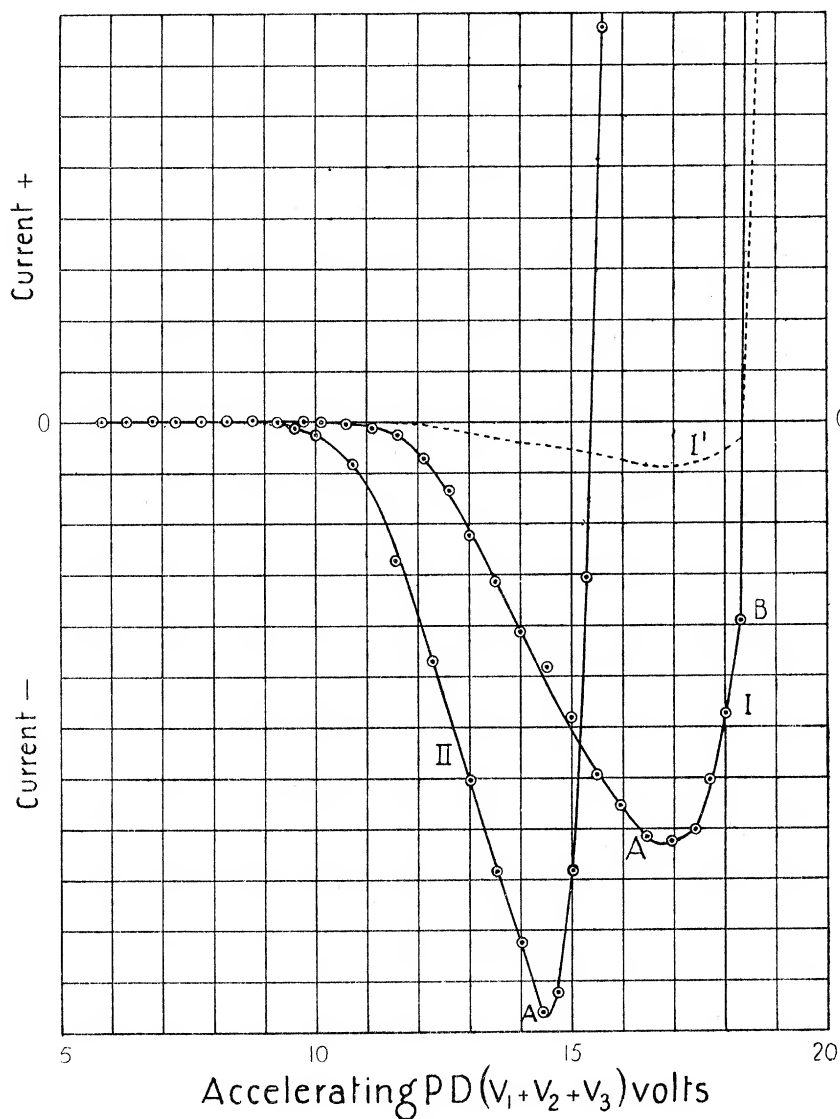


FIG. 2.

in curve I at the point marked B. The observations recorded in this curve are plotted on a smaller scale in curve I' which gives a better idea of the relative magnitudes of the changes which occur at the points A and B. The upward bend at B indicates a sudden increase of positive current and this

change was always preceded by an unsteadiness of the measured current, that is to say, repeated observations under apparently the same conditions were not in good agreement. In some (I--R) curves, taken at higher pressures, the bends at A and B were not so distinctly separated as in curve I. In some instances A and B coincided, and the current changed abruptly from an increasing negative current to a relatively enormous positive current, while in other curves obtained the point A was marked merely by a discontinuity in the negative current and was separated from B by a small fraction of a volt only. A more complete investigation of this effect is recorded in a later section of the present paper.

Fig. 3 represents a series of measurements of the (I+R) currents taken with the collecting electrode about 0.5 mm. from the gauze B. Argon was,

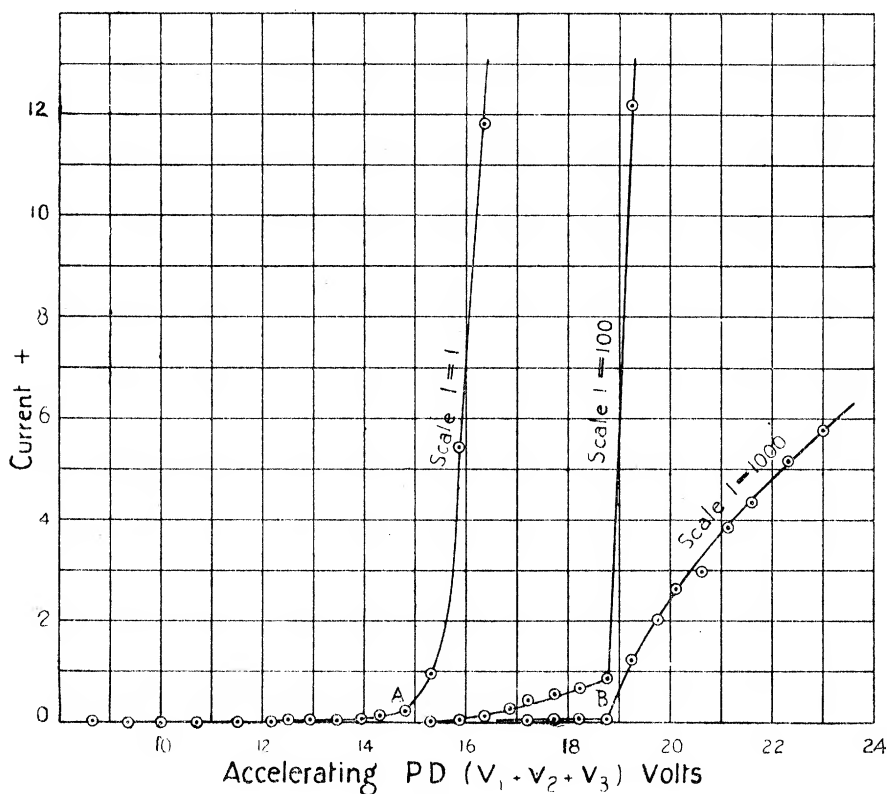


FIG. 3.

as usual, streaming through the apparatus during the observations and the pressure increased gradually from 0.026 mm. 0.031 mm. during the series. In order to show the relative magnitude of the sudden changes in the measured currents the latter are plotted on three different scales which are marked on

the curves. The gradual increase in the positive current at the lower voltages is due to radiation. The point A corresponds to the point A in the (I-R) curves and indicates that positive ions due to ionisation of the argon are beginning to be collected. In the curve given the bend is at about 14.8 volts. A second sharp bend indicating a large increase in the positive current occurs at B which corresponds to the point similarly marked in the curves of fig. 2. It was found that the positions of the two bends A and B varied considerably in different experiments, even in the (I+R) series of observations, so that the arrangement of fields in which $V_4 = 0$ is not a satisfactory one for detecting the beginning of ionisation by collision. This is perhaps to be expected for when V_4 is zero, the detection of ionisation depends mainly on the positive ions formed diffusing out of the space between the gauzes C and N into the space above the latter gauze. It seemed possible that the test for positive ions might be improved by establishing a difference of potential between the gauzes C and N so as to drive positive ions formed in this space through the gauze N, and thus towards the collecting electrode A. Such a field would, of course, retard the electron stream from the filament and would therefore limit the range over which the production of radiation and ionisation could occur when the critical accelerating voltages were reached. This diminishes the amount of radiation or ionisation and so renders the test for radiation less sensitive, but experiments showed that the diminution in the amount of ionisation was more than counterbalanced by the greater proportion of the positive ions formed which were driven to the collecting electrode.

Fig. 4 gives examples of (I-R) and (I+R) curves obtained with a difference of potential of 36 volts between the gauzes C and N. The values of the current are plotted on two scales, the currents in the dotted curves being on one-tenth the scale of the others. At each value of the accelerating voltage (I-R) and (I+R) observations were taken consecutively thus avoiding a difference in the form of the two curves which might arise from any variation of the electron stream, or of the gas pressure. With a potential difference as large as 36 volts opposing the electron stream in the space C-N, the production of radiation (and of ionisation) is restricted to a layer of gas close to the lower gauze C and it will be seen that the photo-electric effect of the radiation on the plate A or on the gauze B was not detectable, for there is no rise in the (I+R) curve, nor fall in the (I-R) curve when the accelerating potential difference is about 10 volts, at which point we have already seen that radiation is produced. An increase in the measured positive currents occurred in both the (I+R) and the (I-R) observations when the accelerating voltage was raised from 13.1 volts to 14.6 volts, showing that

ionisation begins between these limits. These observations were taken with argon streaming through the apparatus at an average pressure of 0.020 mm. The field V_4 in this experiment was sufficiently large to prevent any of the

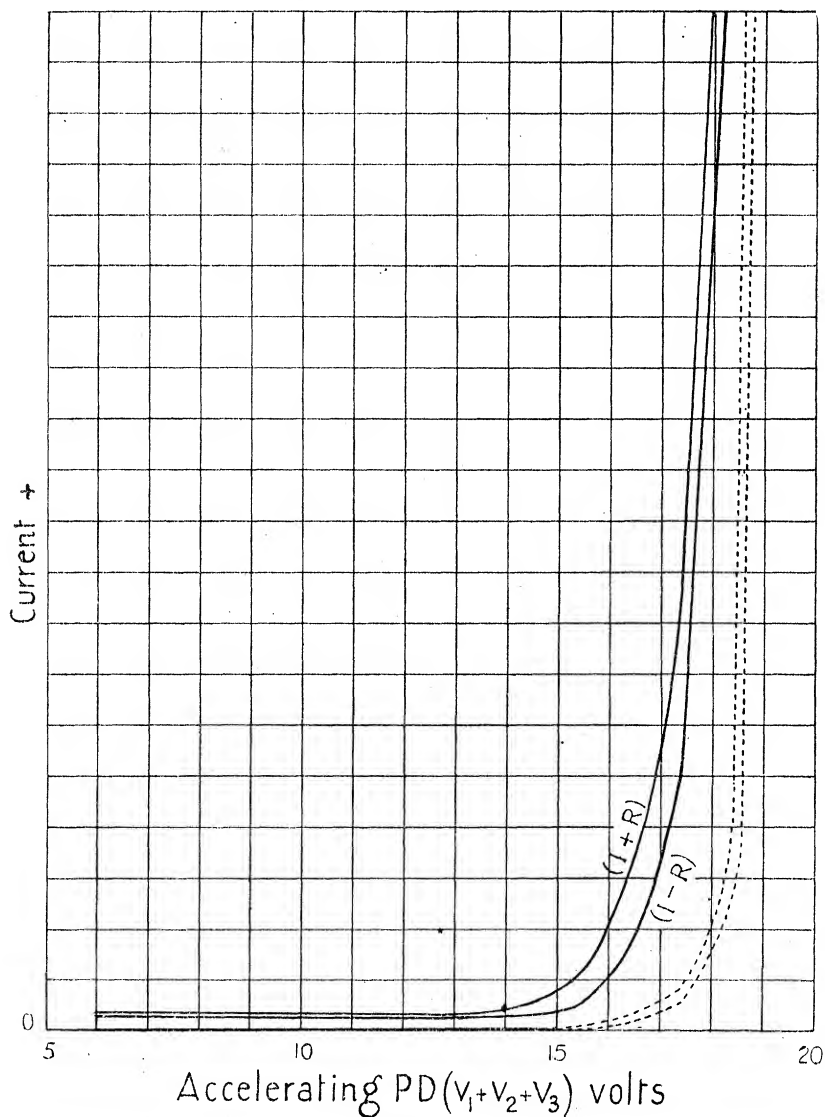


FIG. 4.

electrons from the filament from reaching the collecting electrode; the field V_5 was in the same direction, the difference of potential between the gauzes N and B being 23 volts. Thus, as soon as ionisation occurs, the positive ions are accelerated towards the gauze N and those which pass through this

gauze are further accelerated towards the gauze B. The velocity of the positive ions driven through B should therefore be sufficient for them to travel the small distance separating the plate A from the gauze B (5 mm. in this experiment) even in the case of the (I—R) observations in which the difference of potential V_6 (1.5 volts) opposes them. Under these conditions, therefore, an increasing positive current should be detected as soon as the velocity necessary for ionisation by collisions is reached.

The velocity of the swiftest electrons getting through the gauze C under a given applied accelerating potential difference was determined under the conditions of experiment in which the curves in fig. 2 and fig. 4 were obtained, and it was found in both cases that the fastest electrons had a velocity corresponding to a potential difference 2.0 volts greater than the applied accelerating voltage. The minimum radiation velocity determined from the curves of fig. 2 is thus between 11 and 12 volts, and the minimum ionisation velocity determined from the curves of fig. 4 lies between 15.1 volts and 16.6 volts.

The Exact Determination of the Critical Velocities.

In order to determine as accurately as possible the value of the minimum velocity an electron must have in order to produce radiation on collision, the two gauzes C and N were connected together so that, when the critical potential difference was reached, radiation might be produced throughout a considerable volume of the gas, and the effect to be detected made as large as possible. Further, in order to allow for any small variation in the natural leak of the electrometer system, or gradual change in the electron emission or the gas pressure, corresponding points on the (I+R) and (I—R) curves were obtained alternately. The point where these two curves diverged was taken as the value of the accelerating potential difference at which radiation began. Every series of observations from which a value of this voltage was determined was immediately followed by a determination of the correction to be applied to it, so as to obtain the velocity of the swiftest electrons present. Fig. 5 shows how well marked the divergence point could be made with this method of experimenting. The (I+R) and (I—R) curves clearly separate between the observations at 9 volts and 9.3 volts. After obtaining these curves, observations at voltages between 8.5 volts and 9.5 volts were repeated at intervals of 0.1 volt, and the point of separation was determined as 9.2 volts. The value of the correction was found to be +2.2 volts, giving 11.4 volts as the minimum radiation potential difference. Many determinations of this point, under slightly different conditions of gas pressure and filament temperature, gave values ranging from 11.4 volts to 11.6 volts, and

the mean of these, 11.5 volts, may be taken as the first critical velocity for electrons in argon.

In our paper on helium, we have described a method of determining the first critical potential difference which does not involve a correction for the velocity of emission of the electrons from the glowing filament. This method can be applied to any gas in which the collisions of electrons with

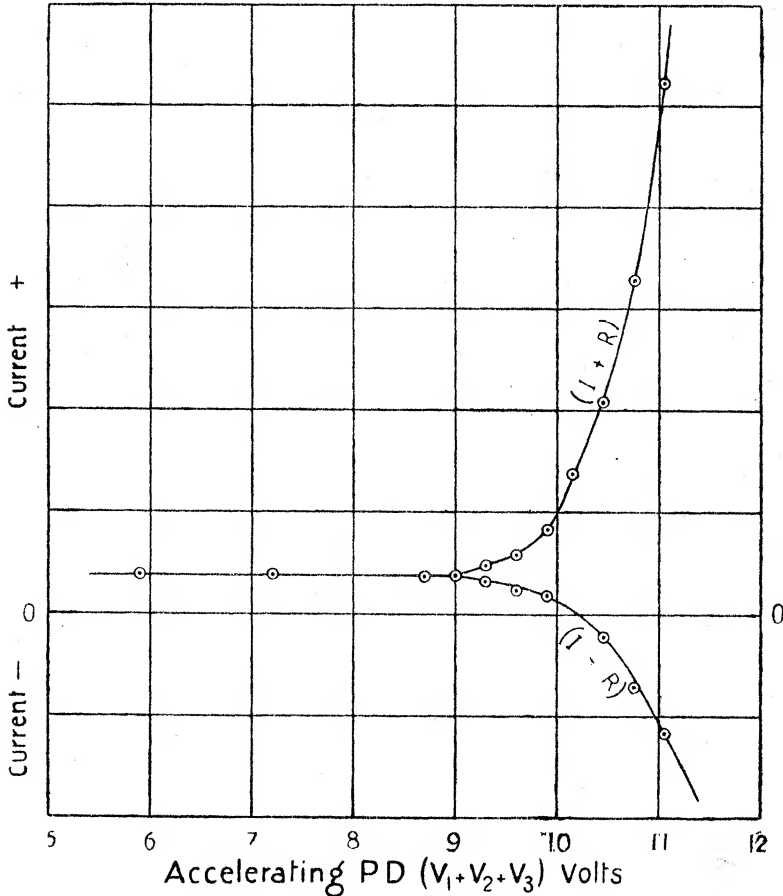


FIG. 5.

the gas atoms are perfectly elastic when the electron velocity is below the critical value. In applying this method to the case of argon, the gauzes C, N, and B were all connected together and maintained at the same potential. The gas pressure has to be fairly high so as to make sure that no electrons pass through this space without colliding with an argon atom. Those electrons which get through the gauze B meet an opposing potential difference between that gauze and the collecting electrode. If, after

colliding with the argon atoms, they pass through B with a velocity greater than this opposing potential difference, they reach the collecting electrode, and cause the electrometer to indicate a negative current, but, if their velocity is less than this amount, they are completely stopped by the retarding field. It follows, therefore, that if this retarding potential difference, V_6 , is fixed at some value less than the first critical potential difference, and the voltage accelerating the electrons is gradually increased, the latter will at some stage be able to get across to the collecting electrode, and a negative current will be detected. If, however, the difference of potential, V_6 , is equal to the first critical potential difference for the gas, electrons with a velocity less than this will be unable to reach the collecting electrode, while, if the accelerating voltage is increased so as to be above this value, the electrons will lose most of their velocity by producing radiation from the argon atoms they collide with, and so will be still unable to reach the collecting electrode. The method of experimenting therefore consists in adjusting the difference of potential, V_6 , until no negative current can be detected by the electrometer as the accelerating voltage is gradually raised. The lowest value of V_6 for which this condition holds gives the first critical potential difference independently of correction.

Experimenting in this way in the case of helium, results were obtained in good agreement with those given by other methods, but, in the present experiments with argon, the results were not so satisfactory. The difficulty appeared to be that, although the pressure was adjusted so that the distance between the gauzes B and C was several times the mean free path of the electron, nevertheless, some of the electrons entering this space with a velocity slightly greater than the minimum radiation potential difference were able to pass through it without losing energy, so that a retarding potential difference, V_6 , greater than the critical voltage, was required to stop them. In these circumstances, the point at which the electrometer detects no current is that at which the number of electrons getting through to the collecting electrode is just equal to the number leaving that electrode owing to the photo-electric effect of the radiation from the argon atoms at which non-elastic collisions have occurred, and the value deduced as the minimum radiation potential difference from such an experiment will be higher than the true value. In the actual experiments with argon, at several different pressures, the values found ranged from 11.5 volts to 12.5 volts. From what has been written above it is probable that the lowest value obtained is most nearly correct, and, as was to be expected, it was obtained from the experiment at the highest pressure (about 1 mm.). These experiments may be taken as showing that, although an electron

moving with a velocity of 11.5 volts is able to produce radiation when it collides with an argon atom, yet it does not always do so, but in some cases may even collide with several argon atoms in succession without appreciable loss of energy. We have recently made some experiments with helium which have shown that in that gas also, an electron moving with a velocity greater than that necessary to produce radiation may collide with a helium atom without loss of energy, but the experiments just described seemed to show that this effect is more marked in the case of argon.

An attempt was also made to obtain the value of the first critical potential difference for electrons in argon by a method similar to that employed by Tate and Foote* in their experiments with metallic vapours. The two gauzes B and N were connected together. The electrons from the filament were accelerated up to the gauze N and there was a small retarding field between the gauze B and the collecting electrode A. Fig. 6 is an example of the

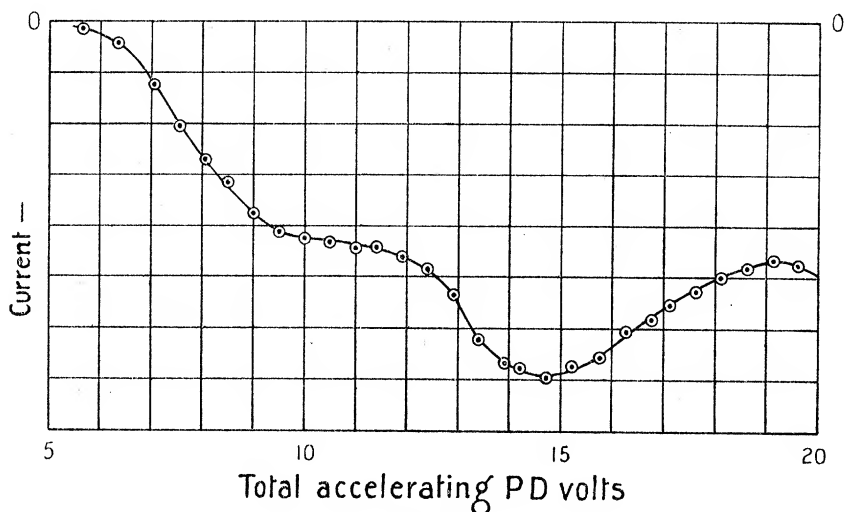


FIG. 6.

curves obtained on plotting the currents measured by the electrometer against the potential difference accelerating the electrons up to the gauze N. The curve slopes gradually downwards until the accelerating potential difference reaches 9 volts. At this point the swiftest electrons on colliding with the argon atoms produce radiation, thereby losing their velocity and being prevented by the small retarding field, V_0 , from reaching the collecting electrode. As the accelerating potential difference is gradually increased beyond this point, more and more of the electrons lose energy in this way

* J. T. Tate and P. D. Foote, 'Phil. Mag.', vol. 36, p. 64 (1918).

and the current curve does not turn downwards until about 11.5 volts is applied. Shortly afterwards, the downward slope of the curve decreases and leads to an upward bend, the point at which the decrease commences, 13.4 volts, indicating the point at which ionisation by collision begins. The average pressure of the argon during these experiments was 0.033 mm. The correction to be added to the applied potential differences in order to give the velocity of the swiftest electrons passing through the gauze N was found to be 2.2 volts. Thus the value of the minimum radiation potential difference for argon is 11.2 volts and the minimum ionisation potential difference is 15.6 volts as deduced from these observations. The position of the second critical point varied considerably in different experiments by this method, probably because the relative magnitudes of the various secondary effects produced by the electron stream depend upon the gas pressure and the arrangement of the electric fields used in any instance. On this account the results obtained by this method were not included in deducing the mean values of the critical velocities for electrons in argon.

The method used to determine accurately the value of the minimum ionisation potential difference was similar to that used in obtaining the results given in the curves of fig. 4. Series of (I + R) observations were taken with a potential difference V_4 of 20 volts or more between the gauzes C and N so as to drive any positive ions formed, through the gauzes N and B where the fields V_5 and V_6 drive them towards the collecting electrode, which for these experiments was lowered to within 1 mm. of the gauze B. When a positive current increasing with the accelerating potential difference is measured under these conditions, it may be due to three causes:—(1) To positive ions formed by ionisation of the argon atoms by electron collisions. (2) To the photo-electric effect of radiation from the argon upon the collecting electrode. (3) To positive ions liberated from the gauze C by the bombardment of the electron stream which is turned back upon it.

It has already been pointed out in connection with fig. 4 that when a considerable difference of potential is applied between the gauzes C and N, the photo-electric effect of the radiation on the collecting electrode, or on the gauze B, could not be detected. This enables us to neglect the second possible cause of the positive current referred to above. The absence of any detectable amount of radiation under these conditions also provides a means of distinguishing between a positive current due to cause (1) and a positive current due to cause (3). The energy with which the electrons, which are turned back in the space between the gauzes C and N, bombard the gauze C, will be smaller the longer the path they traverse in the gas. Therefore, if observations be taken simultaneously for two large values of the potential

difference V_4 , e.g., 20 volts and 36 volts—the electrons being turned back to bombard the same gauze in each case—the measured positive current will be larger in the case of the 20 volts curve or in the case of the 36 volts curve according as it is due to ionisation of the gas, or to the liberation of positive ions from the gauze C.

In any particular series of observations, the approximate position of the point at which a positive current increasing with the accelerating potential difference began was first obtained for some value of the field V_4 , and then further observations over that part of the curve were taken at intervals of 0.1 volt or 0.2 volt. These were immediately followed by a determination of the velocity of the swiftest electrons present when an accelerating potential difference slightly less than the critical value was applied. The correction obtained in this way was added on to the observed critical value and thus the minimum potential difference at which positive ions are produced was determined. A separate experiment was then made to investigate the origin of the positive ions at this voltage, by taking observations for two values of V_4 , simultaneously, as already suggested. These observations showed that as soon as a positive current increasing with the accelerating potential difference was obtained, this current had a larger value when V_4 was 20 volts than when V_4 was 36 volts, thus indicating that increasing the path of the electrons in the gas increased the positive current, which must, therefore, be due to ionisation of the argon atoms and not to positive ions liberated from the gauze C. The minimum potential difference at which positive ions are produced, as already determined, is thus the minimum ionisation potential difference of the gas. Many such determinations were made at various pressures between 0.010 mm. and 0.040 mm. and with different values of the field V_4 . The extreme values found for the ionisation potential difference were 14.7 volts and 15.4 volts but most of the values fell between 15.0 volts and 15.3 volts. The mean of all the values found was 15.1 volts, which may, therefore, be taken as the minimum ionisation potential difference for electrons in argon.

Experiments to Test for Ionisation at the First Critical Velocity.

The experiments already described have shown that radiation is produced when electrons moving with a minimum velocity of 11.5 volts collide with argon atoms, and that when the velocity of the colliding electrons is raised to 15.1 volts, ionisation of the gas occurs. From the results obtained by Franck and Hertz, it has hitherto been thought that argon is ionised by collisions of electrons having a velocity of about 12 volts. It therefore seemed desirable to make a further attempt to detect ionisation at the first

critical potential difference, although the results already recorded show that if any ionisation does occur at this voltage, it is small in amount compared to that which takes place when the impacting electrons have a velocity of 15.1 volts. We were also influenced in making this further test by the fact that towards the end of the experiments described in the last section, trouble was experienced owing to polarisation layers forming on some of the gauzes. The presence of these was detected by the experiments to measure the velocity of the electrons under a given applied potential difference. It was also indicated by the points at which radiation and ionisation were first detected being delayed until the accelerating voltage had been raised several volts above the critical values previously found.

The special test for ionisation at the minimum radiation potential difference was made somewhat in the manner of the experiments by which the value 15.1 volts had been obtained for the minimum ionisation potential difference, but in view of possible polarisation layers the precaution was taken of obtaining two curves simultaneously, one to indicate the point at which radiation commenced, and the other to indicate the point at which positive ions were first detected. In obtaining the former, positive ions were prevented from reaching the collecting electrode, and the effects of radiation alone were studied. The ionisation curve was an (I+R) curve, with the conditions arranged so that the effects of radiation were very small. In order to make the test for ionisation as sensitive as possible, the method of having an electric field in the space between the gauzes C and N, so as to drive the positive ions towards the collecting electrode, was again used, and the collecting electrode was only 1 mm. from the gauze B. The results of one of these experiments, in which the average pressure of the argon was 0.022 mm., are shown in fig. 7. Corresponding points on the two curves were taken consecutively, so as to avoid any errors which might arise from a gradual change in the gas pressure or other conditions. The small positive current which was measured in the observations at the lowest voltages was indeed found to decrease slowly with the time, and this probably accounts for the gradual fall in the ionisation curve at the lower voltages. In both series of observations, the results of which are shown in the curves of fig. 7, the electron stream was turned back between the gauzes C and N, which were at a difference of potential of 18.7 volts. In the ionisation curve the potential differences, V_5 (1.4 volts) and V_6 (1.5 volts), were directed so as to drive positive ions towards the collecting electrode. It will be seen that the presence of these is first indicated between 15.0 volts and 15.8 volts. After each point on the ionisation curve had been determined, the point for the same accelerating potential difference on the radiation curve was found. This

was done by reversing the direction of the difference of potential between the gauzes B and N (V_5), and increasing it so as to prevent positive ions, passing through N, from reaching B. The small field V_6 was also reversed, so that the effect of radiation would be to produce a negative current by acting on the upper surfaces of the gauzes B and N. The effect of the radiation on the upper surface of the gauze B alone has been shown by earlier observations to be very small, except when the field V_4 is very small,

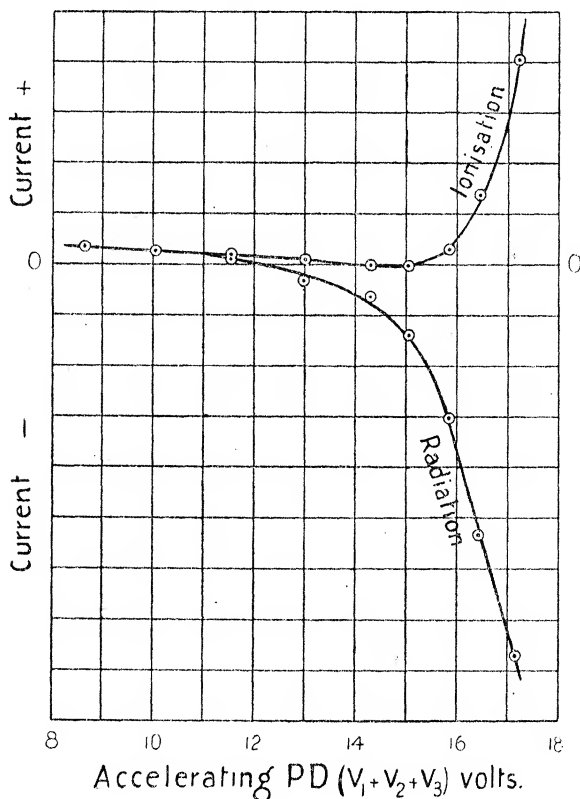


FIG. 7.

but the electrons liberated photo-electrically from the gauze N gave a considerable effect, as can be seen from the radiation curve in fig. 7. The radiation curve diverges from the ionisation curve at about 11.5 volts, which is therefore the point at which radiation begins in both series of observations. The ionisation curve shows no increase of positive current at this point, nor indeed until the accelerating potential difference is raised above 15 volts. There is thus no detectable amount of ionisation of the gas produced at the first critical velocity.

An Investigation of the Relatively Large Increase of Current which Occurs a few Volts above the Minimum Ionisation Potential Difference.

In an earlier section of this paper we have pointed out that when the velocity of the electron stream was increased a few volts above the ionisation potential difference, a large increase occurred in the positive current measured by the electrometer. This is well illustrated in Curve I' of fig. 2. This effect was most marked in those series of observations which were taken with $V_4 = 0$, and it was found that on repeating the observations with gradually decreasing values of the accelerating potential difference, after the sudden increase of current had occurred, the resulting curve did not coincide with the curve for increasing values of the accelerating potential difference. The exact form of the curve obtained depended on the conditions of experiment. Fig 8 shows an (I—R) curve taken with an average pressure of 0.0014 mm. of argon in the apparatus, and with no potential difference between the gauzes

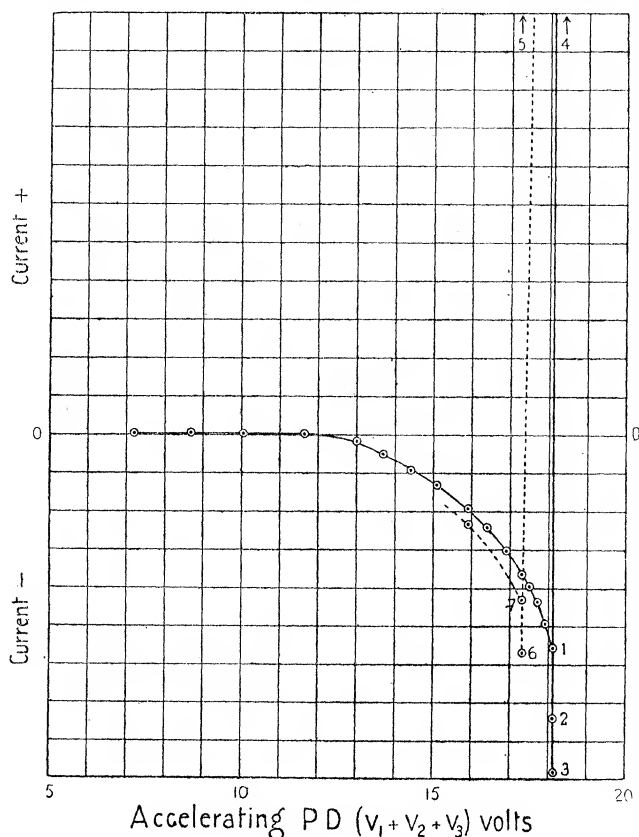


FIG. 8.

The numbers 1-7 refer to the order in which the points were obtained.

C and N. This curve shows that the negative current measured became characteristically unsteady at the accelerating potential difference at which the increase in positive current occurred. The dotted curve represents the currents measured on gradually decreasing the accelerating potential difference. It will be seen that the current remained positive for some time, decreasing with the accelerating voltage to a maximum negative value. Keeping the accelerating potential difference constant, the magnitude of this negative current quickly decreased with time until the measured value became about the same as that observed for the same accelerating voltage on the outward path. The indication of a sudden increase in the radiation at the points 1, 2, 3, in fig. 8 was further investigated by obtaining two curves simultaneously—(a) an (I—R) curve, showing the effects of the positive ions, and (b) a curve showing the effects of the radiation only. The latter was obtained from a series of observations under conditions in which no positive ions could reach the collecting electrode. The resulting curves are shown in fig. 9. In all the observations the field V_4 was zero, and the electrons from the glowing filament were turned back by the field V_5 . In the (I—R) curve, V_6 was 3 volts, while in the radiation curve V_6 was 36.2 volts, the gauze B being negative to the collecting electrode in both cases. Thus in the radiation experiment no positive ions could reach the collecting electrode. The (I—R) curve is similar to those already given and shows the occurrence of radiation, then ionisation, and finally a big increase in the positive current between 20.0 volts and 20.2 volts accelerating potential difference. In the radiation curve the currents are negative all the time, and it will be seen that an enormous increase in the negative current occurs at the same point as that at which the increase in the positive current occurs in the (I—R) curve. Evidently in the latter curve the large effect of radiation is more than counterbalanced by the increased number of positive ions which is collected.

The largely increased current which is obtained in these experiments is similar in its magnitude, in the suddenness with which it takes place, and in the hysteresis which the large current then shows with regard to the accelerating potential difference, to the increase which occurs under certain circumstances when a glowing cathode is used in an evacuated tube with a single anode. This effect was observed some years ago,* and it was found that under the usual conditions the large increase of current across the tube coincided with the appearance of luminosity in the residual gas present. In the present experiments it was found that the sudden increase in the current was accompanied by a faint glow in the gas between the gauzes C and N.

* F. Horton, 'Phil. Trans.,' A, vol. 207, p. 147 (1907).

This glow increased in brightness as the accelerating voltage was increased further, but it was always very faint, especially at the lowest pressures.

The sudden increase in the ionisation of the gas and the accompanying

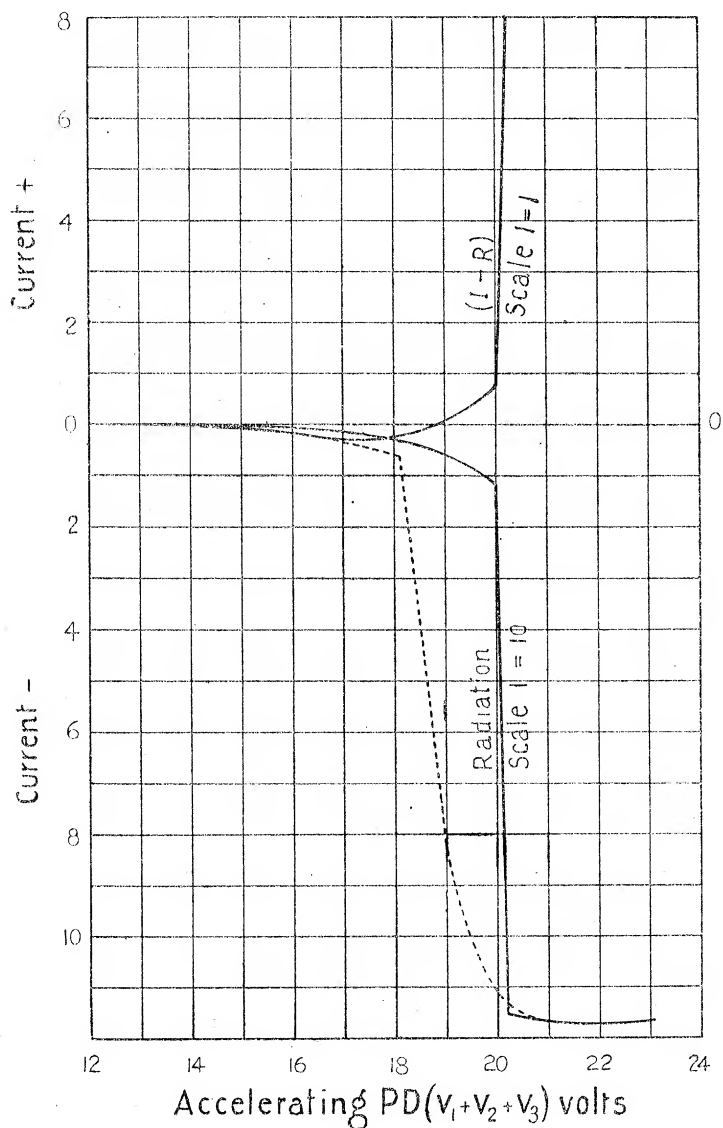


FIG. 9.

luminosity is a phenomenon of considerable interest. A simultaneous increase of radiation and of ionisation might be explained by a sudden neutralisation of the space charge effect, which is due to the mutual repulsion of the electrons preventing the maximum emission from the glowing filament.

The effect of this is considerable only when the cathode is very hot and the emission large, but it is under such conditions that the sudden appearance of the gas luminosity is most marked.

The fact that the sudden increase in the positive current does not begin until a few volts after the electrons are able to ionise the gas, seems to indicate that it is necessary for a certain proportion of positive ions to reach the filament before any considerable neutralisation of the space charge effect and consequent increase in the emission takes place. Evidence of the correctness of this suggestion was provided by the fact that the conditions of experiment which are most favourable to the presence of a considerable number of positive ions near the filament are those under which the lowest values were obtained for the applied potential difference at which the large increase of positive current was observed. On the view that a certain proportion of positive ions is necessary to cause the effect, the hysteresis which the largely increased current shows with respect to the potential difference accelerating the electrons is also explained, for the increased emission will result in an increase in the number of positive ions present; thus as the applied accelerating voltage is reduced neutralisation will continue until the number of positive ions produced by the increased emission falls below that required to maintain the neutralisation.

It must, however, be pointed out that an increased emission of electrons from the filament, however produced, is not sufficient to account for the sudden change of the measured current from a large negative value to a very large positive one, as was often obtained in the (I—R) series of observations. It seems possible that some other factor comes in which increases the proportion of the electrons making ionising collisions at this point. The most obvious of such possible causes is the radiation which is being produced in the gas. Some experiments of Hebb with mercury vapour* make it appear improbable that the radiation produced from a gas acting photo-electrically on the atoms of that gas can ionise them, and such a result is definitely disproved for argon by the experiments we have described, showing that there is no detectable amount of ionisation when radiation is first produced, but it is not impossible that when the accelerating potential difference has reached the minimum ionising value, the proportion of the collisions between electrons and argon atoms resulting in ionisation of the gas is increased when the atoms are exposed to intense 11.5-volt radiation. From the curve of fig. 8, which is typical of many observations of the current in (I—R) experiments, it may be seen that the immediate consequence of the increased emission due to the neutralisation of the space charge effect is an increase

* T. C. Hebb, 'Phys. Rev.,' vol. 11, p. 170 (1918).

of negative current due to radiation. The fact that this increase precedes the detection of the very large positive current which is ultimately measured at the same voltage, supports the suggestion that the radiation itself is a contributory cause of the increased ionisation.

Another possible cause of the greatly increased ionisation of the argon which occurs a few volts above the minimum ionising potential difference, is that a radiation capable of ionising the gas directly may be produced. Sir J. J. Thomson has been able to detect the production of soft Röntgen radiation by the impact of cathode rays with velocities as small as 10 volts.* In the present experiments it is unlikely that the large increase in current is due to a radiation requiring a definite minimum velocity of electrons for its production for the applied potential difference at which the large increase of current occurred varied in different cases from 17 volts to 21 volts. Moreover, if the effect were due to an ionising radiation we should expect to measure larger currents when the collecting electrode was raised some distance above the gauze B than when that distance was very small, but no result which could be attributed to such an effect was observed.

Discussion of Results and Conclusion.

The experiments described in this paper have shown that, when electrons bombard argon atoms, a radiation is first produced from the gas, when the electrons attain a velocity of 11.5 volts, and that ionisation of the gas occurs when the electron velocity is further raised to 15.1 volts. From the quantum relation $eV = hn$ we can calculate the frequency n corresponding to the ionising velocity V , which should be the maximum frequency obtainable from argon for this type of ionisation. Taking $e = 4.77 \times 10^{-10}$ E.S. units and $h = 6.55 \times 10^{-27}$ $\text{gram.cm.}^2/\text{sec.}$, we obtain the value 3.67×10^{15} as the limiting frequency in the spectrum of argon. This corresponds to a wave-length of 817 Å.U. The extreme ultra-violet spectrum of argon has recently been investigated by Lyman,† who has found that the spectrum terminates abruptly near $\lambda 800$, so that the value we have found for the minimum ionisation velocity confirms the spectroscopic evidence.

Although an electron moving with a velocity acquired by falling through a potential difference of 15.1 volts is able to ionise an argon atom on colliding with it, such collisions do not always result in ionisation. A certain amount of evidence has been obtained that, when the electron velocity is greater than the critical ionising value, the fraction of the total number of collisions which result in ionisation is greatly increased by the

* Sir J. J. Thomson, 'Phil. Mag.,' vol. 28, p. 620 (1914).

† T. Lyman, 'Astro.-phys. Jour.,' vol. 43, p. 89 (1916).

presence of intense 11·5 volt radiation, for, as has already been pointed out in connection with the big increase of positive current shown at 18·1 volts in fig. 8, a large increase in the radiation led to an abrupt and very large increase in the ionisation, although no alteration was made in the external conditions. This result suggests that some ionisation may occur at electron velocities below 15·1 volts in the presence of sufficiently intense radiation. That no detectable amount of ionisation is produced below 15·1 volts, in the presence of such intensities of radiation as those to which the argon atoms were subjected in most of the experiments described in this paper, has been proved by special experiments to test for ionisation at the minimum radiation potential difference; and in the case of those experiments in which the argon atoms were exposed to much more intense radiation, and in which the current showed hysteresis in regard to the accelerating potential difference (such as the curves of fig. 8), no evidence of hysteresis below 15·1 volts was ever obtained, a fact which makes it appear unlikely that ionisation does occur below that velocity. Therefore it seems that, though the presence of intense radiation may affect the number of ionising collisions which occur, the minimum ionisation velocity is the same whether the radiation to which the argon atoms are exposed be weak or intense.

An Investigation of the Effects of Electron Collisions with Platinum and with Hydrogen, to ascertain whether the Production of Ionisation from Platinum is due to Occluded Hydrogen.

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In the course of an investigation of the effects of electron collisions with helium atoms,* it was found that positive ions were produced from a positively charged platinum gauze when this was bombarded by electrons with a minimum velocity of about 11 volts. The production of positive ions in this way does not appear to have been observed before for such small velocities of the impacting electrons, though their detection with primary rays of 30 volts

* 'Roy. Soc. Proc.,' A, vol. 95, p. 408 (1919).